Molecular Hydrogen in High-Velocity Clouds

Philipp Richter[1], Kenneth R. Sembach[2,3], Bart P. Wakker[1]

and

Blair D. Savage[1]

ABSTRACT

We present *Far Ultraviolet Spectroscopic Explorer* (FUSE) observations of interstellar molecular hydrogen (H_2) in two Galactic high-velocity clouds (HVCs). Molecular hydrogen absorption is detected in the Magellanic Stream (abundance $\sim$ 0.3 solar) toward the Seyfert galaxy Fairall 9 in the lowest three rotational states ($J = 0-2$) at $v_{\rm LSR} = +190$ km s^{-1}, yielding a total H_2 column density of log N(H_2)$= 16.40^{+0.26}_{-0.53}$. In contrast, no H_2 absorption is seen in the high-velocity cloud Complex C (abundance $\sim$ 0.1 solar) toward the quasar PG 1259+593 (log N(H_2)$\leq$ 13.96 at $v_{\rm LSR} = -130$ km s^{-1}), although both HVCs have similar H I column densities on the order of log N(H I)$\approx$ 20. Weak H_2 absorption is detected in the Intermediate-Velocity Arch (IV Arch; abundance $\sim$ 1.0 solar) toward PG 1259+593 (log N(H_2)$= 14.10^{+0.21}_{-0.44}$ at $v_{\rm LSR} = -55$ km s^{-1} and log N(H I) = 19.5). It thus appears that metal- and dust-poor halo clouds like Complex C are not able to form and maintain widely distributed H_2, whereas metal and dust-rich halo clouds like the IV Arch can maintain H_2 even at low H I column densities.

Subject headings: ISM: clouds – ISM: abundances – quasars: absorption lines – quasars: individual (Fairall 9, PG 1259 +593) – Galaxy: halo

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[1]Department of Astronomy, University of Wisconsin-Madison, 475 N. Charter Street, Madison, WI 53706; richter@astro.wisc.edu

[2]Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218

[3]Current address: Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218

1. Introduction

The *Far Ultraviolet Spectroscopic Explorer* (FUSE) is the first instrument to be used to systematically study atomic and molecular absorption lines in Galactic halo clouds in the important far-ultraviolet (FUV) spectral range ($\lambda < 1150$ Å). These halo clouds are seen in H I 21cm emission at radial velocities that do not match a simple model of differential Galactic rotation. A separation is traditionally made between high-velocity clouds (HVCs; $|V_{\rm LSR}| > 90$ km s^{-1}) and intermediate-velocity clouds (IVCs; 30 km s^{-1} $< |V_{\rm LSR}| <$ 90 km s^{-1}). The presence of molecular material would give important new insights into the physical conditions in the interiors of these clouds, and would allow the study of molecular gas under conditions that are likely to be very different from those in the disk of the Milky Way. In addition, it has been proposed that dense molecular regions in the Galactic halo could serve as birth places for the population of young B-type stars found in the Milky Way halo (Conlon et al. 1992), or even as candidates for baryonic dark matter (e.g., de Paolis et al. 1995; Kalberla et al. 2000).

Until recently, most searches for molecular gas in HVCs were restricted to observations of CO (e.g., Wakker et al. 1997; Akeson & Blitz 1999), but neither CO emission nor absorption was found. In their survey of HCO^+ absorption in HVCs toward 27 quasars, Combes & Charmandaris (2000) reported one tentative detection, but this case has not been confirmed yet. The most abundant molecule in the Universe, molecular hydrogen (H_2), could not be observed in HVCs and IVCs before 1996 because of the lack of suitable space-based instrumentation to study H_2 absorption in the Galactic halo at wavelengths between 900 and 1130 Å. With new FUV instruments such as FUSE and the *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer* (ORFEUS), this wavelength range has now become accessible, and recent studies of various Galactic halo cloud complexes have unveiled the presence of diffuse H_2 in both HVCs (Richter et al. 1999; Sembach et al. 2001) and IVCs (e.g., Gringel et al. 2000; Richter et al. 2001a), albeit at low column densities ($\log N(H_2) \leq 17$). While diffuse H_2 appears to be a rather widespread constituent in the more nearby and metal-rich IVCs, H_2 in HVCs has been detected only in two cases (Richter et al. 1999; Sembach et al. 2001). However, H_2 measurements of gas in HVCs are more difficult due to the limited availability of suitable background sources at large distances from the Galactic plane.

2. The Magellanic Stream and Complex C

In this paper we investigate the molecular hydrogen content in the Magellanic Stream toward the Seyfert galaxy Fairall 9 ($l = 295\overset{\circ}{.}1, b = -57\overset{\circ}{.}8$; $V = 13.83$; $z = 0.047$) and in high-velocity cloud Complex C toward the quasar PG 1259+593 ($l = 120\overset{\circ}{.}6, b = +58\overset{\circ}{.}1$;

$V = 15.84$; $z = 0.478$). Figure 1 shows the location of these two sight lines plotted on the Magellanic Stream and Complex C H I 21cm emission maps (Hulsbosch & Wakker 1988; Bajaja et al. 1985; Morras et al. 2000). The Magellanic Stream has a metallicity of ~ 0.3 solar (Gibson et al. 2000; Lu et al. 1998) and is believed to be tidally torn out of the Small Magellanic Cloud (SMC). Sembach et al. (2001) have detected H_2 absorption in the Leading Arm of the Magellanic Stream toward the Seyfert galaxy NGC 3783 with log $N(H_2) = 16.80 \pm 0.10$. Toward Fairall 9, Parkes 21cm emission line data (17$'$.0 beam) show two blended H I components at $v_{\rm LSR} = +149$ and $+195$ km s^{-1} with a total integrated H I column density of log $N = 19.97 \pm 0.01$ (Gibson et al. 2000). For Complex C, Wakker et al. (1999) and Richter et al. (2001b) find elemental abundances of ~ 0.1 solar, suggesting that Complex C represents the infall of intergalactic material onto the Milky Way, but Gibson et al. (2001) reported abundances for Complex in other directions that vary between 0.08 and 0.44 solar. Murphy et al. (2000) did not find H_2 absorption in Complex C toward Mrk 876 (log $N(H_2) \leq 14.30$). Toward PG 1259+593, Effelsberg 21cm data (9$'$.1 beam) show Complex C H I 21cm emission at $v_{\rm LSR} = -130$ km s^{-1} with log $N(\text{H I}) = 19.92 \pm 0.01$ (Wakker et al. 2001), but other instruments at lower resolution (see Richter et al. 2001b) yield lower column densities observing the same direction, indicating that there is sub-structure in Complex C on $10-20$ arc minute scales. The H I profiles toward PG 1259+593 (sampling Complex C) and Fairall 9 (sampling the Magellanic Stream) are shown in the top panels of Figure 2.

3. FUSE Observations and Data Analysis

Four optical channels are available on FUSE, two SiC channels from 905 to 1100 Å, and 2 LiF channels covering 1000 to 1187 Å (for instrument descriptions and performance information see Moos et al. (2000) and Sahnow et al. (2000)). FUSE observations of Fairall 9 were conducted 7 July 2000, and observations of PG 1259+593 were performed between February 2000 and March 2001. The observations were obtained using the large aperture (LWRS) and the photon address mode, providing spectra at a resolution of ~ 25 km s^{-1} (FWHM). Total integration times were ~ 35 ks (Fairall 9), and ~ 400 ks [4] (PG 1259+593). The data were reduced with the CALFUSE (v.1.8.7) calibration pipeline and rebinned to 8 km s^{-1} wide pixels. The wavelength calibration (accurate to approximately ± 10 km s^{-1}) is based on aligning various atomic absorption lines with the H I 21cm emission data.

For PG 1259+593, the average flux in the FUSE spectrum is $\sim 2\times10^{-14}$ erg cm^{-2} s^{-1} Å^{-1}. The flux is almost constant over the wavelength range sampled by FUSE, and the typical

[4] After correction for event bursts in the raw data.

signal-to-noise ratio (S/N) is ~ 17 per pixel element after rebinning. The average flux in the Fairall 9 spectrum is also $\sim 2 \times 10^{-14}$ erg cm^{-2} s^{-1} Å^{-1}, so that with $t_{\rm obs} = 35$ ks the S/N is ~ 3 at most wavelengths. This is too low to accurately measure absorption lines with equivalent widths (W_λ) less than ~ 80 mÅ at wavelengths < 1040 Å, where numerous atomic and molecular lines cause severe blending problems. For $\lambda > 1040$ Å, however, the flux in the Fairall 9 spectrum rises to $\sim 8 \times 10^{-14}$ erg cm^{-2} s^{-1} Å^{-1} due to intrinsic Ly β emission from Fairall 9 itself. This allows us to study molecular hydrogen toward Fairall 9 in the well-separated Lyman $0-0$, $2-0$, $3-0$ and $4-0$ bands at an average S/N of ~ 6 per rebinned pixel element. For the following analysis we used data from the SiC 2A, LiF 1A, and LiF 1B data segments, which provide higher S/N and better resolution than the SiC 1B, LiF 2B, and LiF 2A data.

4. H_2 Measurements

In the spectrum of Fairall 9, we find H_2 absorption in lines from the rotational levels $J = 0, 1$, and 2 in the Magellanic Stream at $v_{\rm LSR} = +190$ km s^{-1}. We have selected 14 lines that have sufficient S/N for a reliable analysis. Low-order polynomials were fit to the continua and equivalent widths were measured by fitting single component Gaussians to the H_2 lines. H_2 absorption line profiles are shown in Figure 2, and equivalent widths are listed in Figure 3. There is an indication that the H_2 line profiles have a second weak component at $v_{\rm LSR} = +149$ km s^{-1}, similar to the H I emission pattern. The data quality, however, is not good enough to separate these two components, and the observed equivalent widths are clearly dominated by the $+190$ km s^{-1} absorption. Almost no H_2 absorption is seen in the local Galactic gas at 0 km s^{-1}. H_2 column densities for the Magellanic Stream were derived by fitting the absorption lines from the individual rotational states to a curve of growth with $b = 5.0^{+3.4}_{-1.2}$ km s^{-1}, which represents the best fit to the data. We obtain logarithmic column densities, log $N(J)$, of log $N(0) = 15.86^{+0.40}_{-0.46}$, log $N(1) = 16.22^{+0.21}_{-0.54}$, log $N(2) = 15.04^{+0.28}_{-0.23}$, and log $N(3) \leq 14.45$ (3σ). The total H_2 column density is log $N = 16.40^{+0.28}_{-0.53}$, and the average fraction of hydrogen in molecular form is $f = 2N({\rm H_2})/[N({\rm H\,I})+2N({\rm H_2})] = 5.4\times10^{-4}$, using the total H I column density for the Magellanic Stream from the Parkes data shown in Figure 2. We derive an excitation temperature of $T_{\rm ex} = 142 \pm 30$ K by fitting the rotational level populations of $J = 0, 1$, and 2 to a single Boltzmann distribution (see Figure 3). [5] The temperature is very similar to that found in the Leading Arm of the Magellanic Stream by Sembach et al. (2001; $T_{\rm ex} = 133^{+37}_{-21}$ K). Possibly, both values represent the kinetic

[5]The single temperature fit indicates that the ortho-to-para H_2 ratio is in local thermodynamical equilibrium.

temperature of the gas in which the H_2 resides. These temperatures are roughly twice as high as the kinetic temperatures found in the Milky Way disk (Savage et al. 1977), but are more similar to those found for high-latitude clouds (Shull et al. 2000).

Toward PG 1259+593, atomic absorption is present at Complex C velocities near $v_{\rm LSR} = -130$ km s^{-1} (Richter et al. 2001b), but no significant H_2 absorption is detected (Figure 2). [6] We analyze the strongest of the H_2 absorption lines in the Werner band $J = 0$ and 1 rotational levels at $\lambda = 985.6$ and 1008.6 Å, deriving 3σ detection limits on the order of 25 mÅ. From that we determine a 3σ upper limit of log N(H_2)≤ 13.96 for the total H_2 column density in Complex C, assuming that these lines lie on the linear part of the curve of growth. Using the Effelsberg H I data, we find f(H_2)$\leq 2.2 \times 10^{-6}$ (3σ). While the FUSE data of PG 1259+593 show no evidence for H_2 in Complex C, very weak H_2 absorption is detected in 6 $J = 0 - 2$ lines at $v_{\rm LSR} = -55$ km s^{-1} (see Figure 2), related to gas of the Intermediate Velocity Arch (IV Arch) in the lower Galactic halo (see Richter et al. 2001b). This finding is consistent with a previous detection of H_2 in this IVC toward the halo star HD 93521 (Gringel et al. 2000) in roughly the same direction of the sky. For this component, we find a total H_2 column density of log $N = 14.10^{+0.21}_{-0.44}$, assuming that the lines fall on the linear part of the curve of growth. [7]

5. Discussion

Molecular hydrogen absorption in HVCs has now been detected in three HVC sight lines. The first detection of H_2 in HVC gas was reported by Richter et al. (1999) for the high-velocity gas in front of the Large Magellanic Cloud (LMC) toward HD 269546. The second detection was that of Sembach et al. (2001), who found H_2 in the Leading Arm of the Magellanic Stream in the direction of NGC 3783. The results presented here show that H_2 is also present in the main body of the Magellanic Stream, but probably not in Complex C.

A preliminary analysis of more than 100 FUSE spectra of quasars, AGNs, and halo stars (including several sightlines passing through Complex C) gives also no evidence for the existence of H_2 in HVCs other than the Magellanic Stream and in the cloud in front of the LMC, but shows the presence of H_2 absorption in IVCs in at least 15 spectra (H_2 detections

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[6] The only noteworthy H_2 feature seen at Complex C velocities is that in the Werner Q(2),0-0 line (see Fig. 2), but this absorption is probably a contaminating intergalactic absorber or an instrumental artifact since there is no H_2 absorption seen in other $J = 2$ transitions.

[7] Because of the small number of lines and the resulting large uncertainties for the individual column densities, $N(J)$, a reliable estimate for $T_{\rm ex}$ is not possible.

include the IV Arch, the LLIV Arch, Complex gp, and the IV Spur; see Richter 2001c). It appears that diffuse H_2 is rather widespread in IVCs, but present only in certain HVCs. Most likely, this is a metallicity effect: IVCs tend to have nearly solar abundances (e.g., Richter et al. 2001a), while abundances in HVCs are as low as ~ 0.1 solar (e.g. Complex C; Wakker et al. 1999; Richter et al. 2001b). The abundances and distances measured in IVCs so far support the idea that they represent the returning, cooled gas of a "Galactic fountain" (Houck & Bregman 1990). If so, the H_2 found in IVCs must have formed *in* the halo, because it is unlikely that molecular material survives the violent processes that ejects the gas into the halo. A fraction of the available heavy elements is incorporated into dust grains, on whose surface the H_2 formation proceeds most efficiently (e.g., Pirronello et al. 1999). Thus, metal and dust-deficient clouds should have much lower H_2 formation rates than those with higher abundances. The depletion of Fe II and Si II in the IV Arch (Richter et al. 2001b), in the Magellanic Stream (see Sembach et al. 2001), and in the HVC in front of the LMC indicates that these clouds contain dust grains, in contrast to Complex C, where the abundance pattern suggests that Complex C contains little, or no dust at all (Richter et al. 2001b). The detections of H_2 in IVCs and HVCs that contain heavy elements in comparison to the H_2 non-detections in metal- and dust-deficient clouds like Complex C therefore suggest that the H_2 formation in Galactic halo clouds is very sensitive to the dust abundance. Metal- and dust-deficient clouds like Complex C are probably not able to form and maintain widely distributed H_2 gas. However, if the molecular material in metal-poor halo clouds is highly concentrated in small, dense clumps, where the H_2 formation rate (increasing with density) can compete with the photo-dissociation (which is reduced by H_2 line self-shielding), it may remain hidden from observation.

In the case of the Magellanic Stream, Sembach et al. (2001) have suggested that the H_2 may have formed in the Magellanic system and has survived the tidal stripping. In view of the overall presence of H_2 in IVCs, however, it is just as likely that the H_2 has formed in situ on dust grains during the 2 Gyr orbital period of the Magellanic Stream. Possibly, H_2 in the Magellanic Stream and in IVCs forms quickly in small, compact cloudlets and then is dispersed into a larger volume by cloudlet collisions or other disruptive processes. The diffuse molecular gas in the Magellanic Stream and in IVCs then may trace a more dense (but yet undetected) molecular gas phase in the halo in which star formation might occur (see Dyson & Hartquist 1983; Conlon et al. 1992).

Clearly, more FUV absorption line measurements are desirable to further investigate the molecular gas phase in the Galactic halo. A systematic study of H_2 in IVCs and HVCs could also help to characterize the formation and dissociation processes for H_2 in diffuse gas in environments at low metallicities and moderate FUV radiation fields, such as in low surface brightness galaxies and intergalactic H I clouds.

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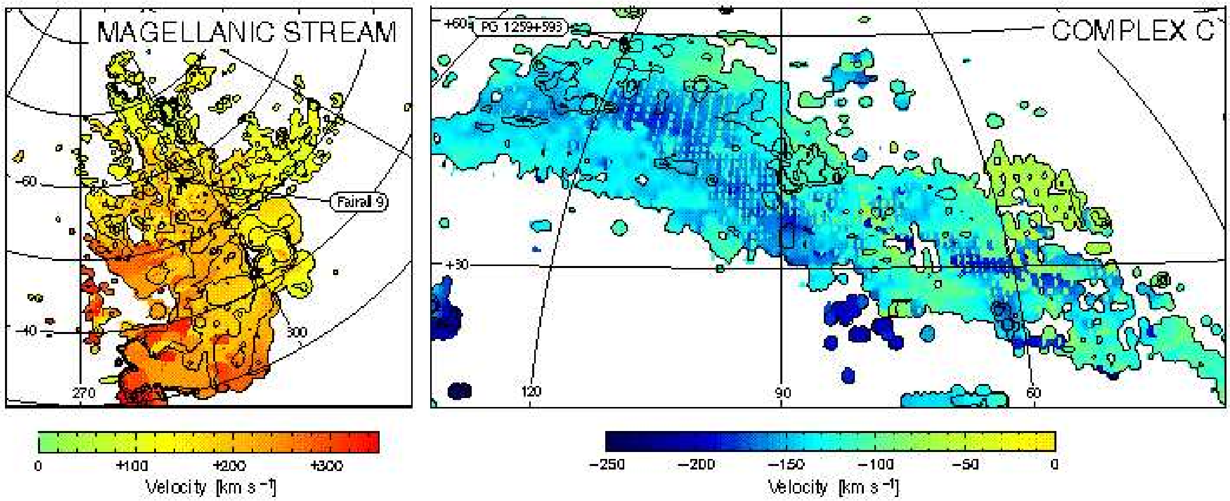
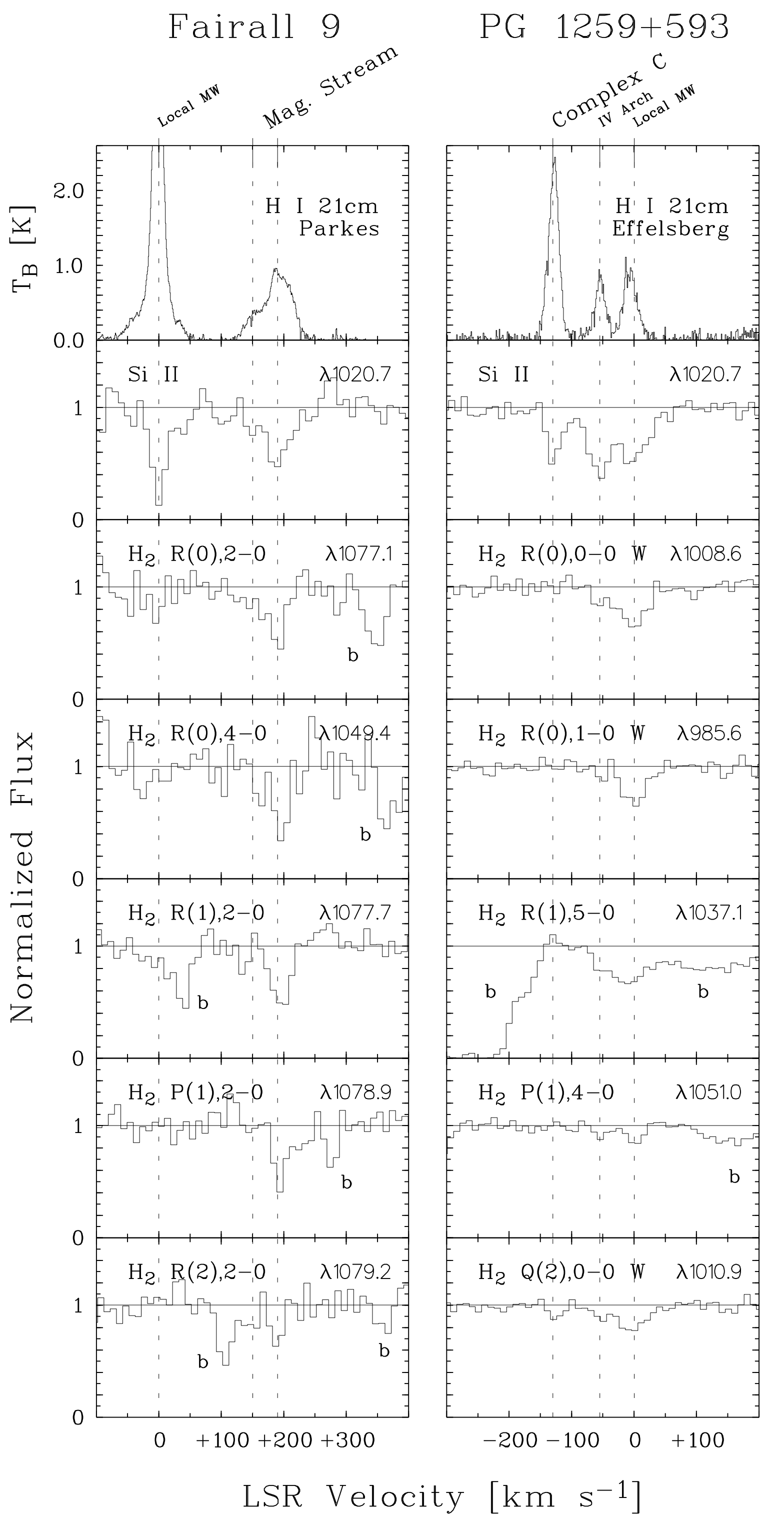


Fig. 1.— H I 21cm maps (l, b) of the Magellanic Stream (MS; left panel) and Complex C (right panel; for references see text). The sight lines toward Fairall 9 (MS) and PG 1259+593 (Complex C) are labeled in the plot. Contours represent H I column densities of $0.3, 2.0, 6.5$ and 13.0×10^{19} cm^2. The grey (colour) scale shows velocity [A higher quality version of this Figure is available on request].



Fairall 9
PG 1259+593
Local MW
Mag. Stream
Complex C
IV Arch
Local MW
H I 21cm
Parkes
H I 21cm
Effelsberg
T_B [K]
Si II λ1020.7
H2 R(0),2–0 λ1077.1
H2 R(0),0–0 W λ1008.6
H2 R(0),4–0 λ1049.4
H2 R(0),1–0 W λ985.6
H2 R(1),2–0 λ1077.7
H2 R(1),5–0 λ1037.1
H2 P(1),2–0 λ1078.9
H2 P(1),4–0 λ1051.0
H2 R(2),2–0 λ1079.2
H2 Q(2),0–0 W λ1010.9
Normalized Flux
LSR Velocity [km s−1]

Fig. 2.— Interstellar H_2 absorption line profiles from the FUSE spectra of Fairall 9 (left panel) and PG 1259+593 (right panel). H I emission line spectra from Parkes and Effelsberg are plotted in the uppermost box. For comparison, Si II λ1020.7 line profiles are also shown. The various absorption components are labeled above the boxes; H_2 transitions from the Werner band are labeled with 'W'. In the spectrum of Fairall 9, H_2 absorption in the Magellanic Stream is clearly visible at $v_{\rm LSR} = +190$ km s^{-1}. No H_2 is seen in Complex C at $v_{\rm LSR} = -130$ km s^{-1} in the spectrum of PG 1259+593, but weak H_2 absorption is present in the IV Arch component at $v_{\rm LSR} = -55$ km s^{-1}. Blending lines from other species are marked with 'b'.

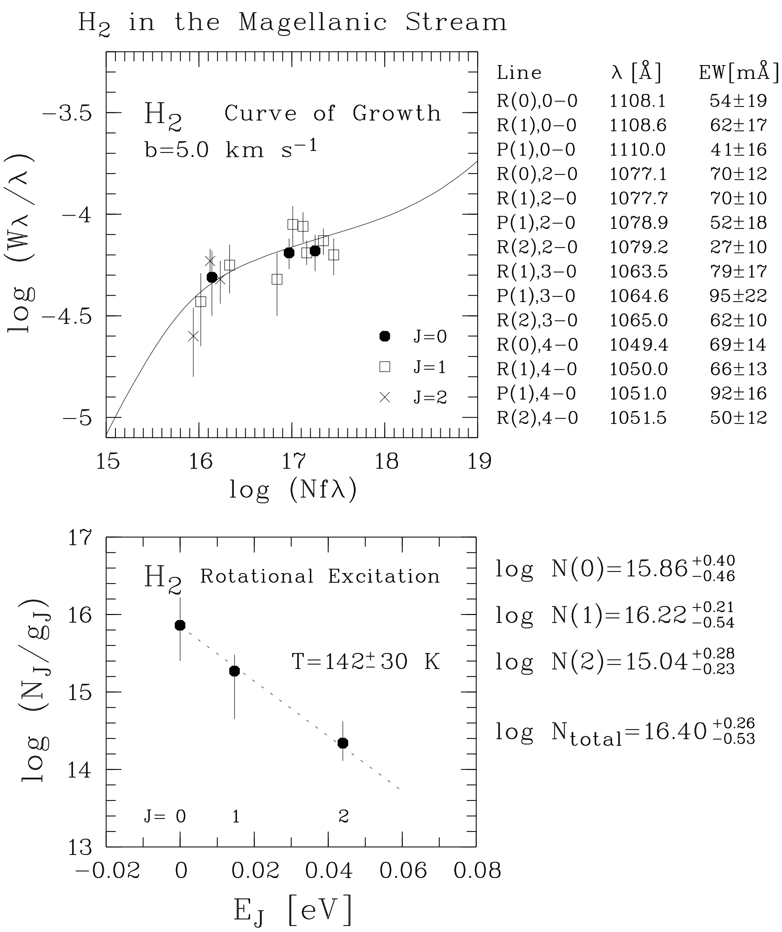


Fig. 3.— Empirical curve of growth for the measured H_2 absorption lines in the Magellanic Stream toward Fairall 9 (upper panel). Wavelengths and equivalent widths of these lines are listed on the right-hand side next to the plot. The lower panel shows the rotational excitation of the H_2 gas in the Magellanic Stream, equivalent to a Boltzmann temperature of $T_{ex} = 142 \pm 30$ K. H_2 column densities are given on the right-hand side next to the plot.